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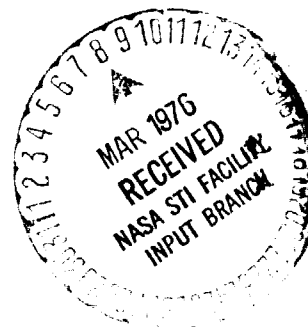
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**PERFORMANCE OF SOME MINIATURE PRESSURE TRANSDUCERS
SUBJECTED TO HIGH ROTATIONAL SPEEDS AND
CENTRIPETAL ACCELERATIONS**

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ABSTRACT

The performance characteristics of several miniature pressure transducers have been determined at centripetal accelerations up to 11 200 g's at a rotational speed of 23 000 rpm. The variation in centripetal acceleration was produced by changing radial position of the transducer relative to the center of rotation.

Residual zero outputs and transducer sensitivities were determined at 23 000 rpm and compared with those determined at 0 rpm. Changes of sensitivities due to effects of centripetal accelerations up to 11 200 g's at a rotational speed of 23 000 rpm are less than 0.2 percent for the $1.7 \times 10^5 \text{ N/m}^2$ (1.7 atm.) full scale range transducers and average about 0.5 percent for the $0.3 \times 10^5 \text{ N/m}^2$ (0.3 atm) range transducers. Changes of residual zero also depend upon transducer range. The $1.7 \times 10^5 \text{ N/m}^2$ (1.7 atm) range transducers exhibited zero shifts of no greater than 0.7 percent of full scale for all g forces up to 11 200 g's while $0.3 \times 10^5 \text{ N/m}^2$ (0.3 atm) range transducers shifted up to $3\frac{1}{2}$ percent.

The actual pressures at the various transducer locations differ from the center line impressed pressures due to a rotational effect. Corrections for this effect were made.

A brief description of the test apparatus is included.

INTRODUCTION

In the development of high performance aircraft turbines, static pressure measurements on the surface of turbine blades, and total and static pressure measurements of turbine coolants are necessary. One method for making these measurements is to place pressure transducers inside the rotating turbine shaft and run tubing to test points on the turbine blade surfaces and blade cooling passages. Because the pressure taps are off center centrifugal pumping corrections must be taken into account with this technique. A slip ring assembly or other signal transfer device is required to supply power to the transducers and transfer the output signals from the rotating shaft.

Previous work with rotating pressure measuring systems reported in Refs. 1 and 2 indicated errors of up to 8 percent using variable reluctance pressure transducers at rotational speeds of 9000 rpm and placed 2.86 centimeters from the centerline of rotation resulting in 2600 g's. More recent requirements at higher shaft speeds necessitated the investigation of the performances of other types of transducers for both on and off center-line designs.

Locations of pressure transducers along the shaft centerline minimizes the centripetal acceleration imposed on a transducer but leads to design complications because of the length of such a configuration if many transducers are needed. These complications include limited applicability to different turbine test rigs because of the available space or limitations in the number of measuring channels to be used, and shaft dynamics problems due to the lower stiffness of long assemblies.

The alternate arrangement, a number of transducers located in a cylindrical housing at a small radius from the centerline much like cartridges in a revolver type gun, leads to a shorter, more compact design. This compact design tends to minimize the design problems cited above and may lead to a simpler system for distributing pressure tubes and electrical wires to the various transducers. However, the acceptability of this configuration depends upon demonstration of acceptable performance of the pressure transducer under the resultant centripetal acceleration.

In order to answer questions concerning effects of centripetal acceleration on transducer performance a small test facility was designed and built that had the capability of rotating pressure transducers either on centerline or at radii up to 1.9 centimeters ($3/4$ in.) at rotational speeds up to 23 000 rpm. Several miniature pressure transducers were tested, some on centerline only and some both on centerline and at radial positions of 0.6 centimeter ($1/4$ in.), 1.3 centimeters ($1/2$ in.), and 1.9 centimeters ($3/4$ in.).

The centripetal acceleration developed at 23 000 rpm and a radius of 1.9 centimeters is 11 200 g's where 1 g is the free fall constant equal to 9.806 m/s^2 .

PRESSURE TRANSDUCER SPIN TEST FACILITY

A spin test apparatus consisting of a 10 centimeter diameter air driven turbine, a pressure transducer test chamber, and a four-ring mercury slip ring transmitter was designed and assembled. Fig. 1 shows the complete apparatus and Fig. 2 is a photograph of the apparatus partially disassembled showing the 0.6 centimeter radius transducer holder. Fig. 3 shows the centerline and 1.3 and 1.9 centimeter radius holders as well as one of the transducers tested and a tube for pressurizing the transducer test chamber. Fig. 4 is a schematic drawing of the salient parts of the spin test apparatus. Accurately known pressures were supplied to the transducer while rotating. The pressures were developed with a self-regulating pneumatic dead weight tester and the pressure was transferred from a stationary stanchion to the rotating shaft and to the transducer through hypodermic tubing which rotates with the shaft. The hypodermic tubing rotates in a tightly fitting nonrotating glass filled teflon bushing, thus making a pressure seal. A detail of the pressure seal is shown on Fig. 4. This seal is effective at high rotational speeds because of the low surface velocity of the hypodermic tubing due to its small diameter (0.048 mm) and the self-lubricating quality of the glass filled teflon bushing. Occasionally some leakage was observed due to bushing wear. Leakage was monitored by observing the record of the transducer output signal versus shaft speed on an x-y recorder. The leak was stopped by tightening a nut which applied increased compression to the bushing.

The slip ring assembly was a commercially available unit that uses liquid mercury to bridge the rotating-nonrotating gap. This assembly had only four separate rings so that only one transducer could be tested at a time. The consistency of the slip ring resistance was checked by shorting both signal and excitation terminals at the slip ring inputs and monitoring the resistance level with an impedance bridge at speeds up to 23 000 rpm. No change in resistance was detected.

TRANSDUCERS TESTED

Table 1 lists the static, nonrotating performances parameters for the various pressure transducers tested. The test transducers have full scale ranges of $4 \times 10^5 \text{ N/m}^2$ (4 atm), $1.7 \times 10^5 \text{ N/m}^2$ (1.7 atm), and $0.3 \times 10^5 \text{ N/m}^2$ (0.3 atm). All transducers tested have four active arm Wheatstone bridges diffused into a silicon chip and all diaphragms are silicon. The reason for the great difference in sensitivities of the A and B transducers is that the A transducers have built in amplification. Observation of the sensitivities and nonrepeatability data for the B transducers indicate that the $0.3 \times 10^5 \text{ N/m}^2$ transducers are merely down ranged $1.4 \times 10^5 \text{ N/m}^2$ or $1.7 \times 10^5 \text{ N/m}^2$ transducers. This accounts for both the lower sensitivity and greater nonrepeatability of the $0.3 \times 10^5 \text{ N/m}^2$ units.

Fig. 5 shows the magnitude of the residual zero shift with time with no rotation for four B transducers. The information presented on this figure gives an indication of the long term zero drift and

can be compared later with the magnitude of the zero shift with g level. The long term zero drift of the A transducer was not measured.

TEST PROCEDURE

Rotating data were obtained for the A and B transducers and are presented in the next section. Since the B transducers seemed to be most suitable both in size and performance, more extensive testing was done on these transducers.

Transducer outputs were recorded versus shaft speed on an x-y recorder. Fig. 6 is a tracing of a typical record of raw data with no correction applied. In order to determine sensitivity and zero shifts versus "g" level a separate run was made on each transducer at various radii as well as on center line. A run consists of two parts: (1) rotating the transducer up to 23 000 rpm with zero pressure applied, and then (2) rotating the same transducer under the same conditions except that full-scale pressure was applied. Pre- and postrun readings of output corresponding to zero applied pressure and output corresponding to full-scale applied pressure were made with a digital voltmeter. The DVM supplied high resolution initial and final transducer output readings and the x-y recorder supplied the change of output due to rotation.

One of the primary considerations in these tests was the alignment of the transducer so that the plane of the transducer diaphragm was perpendicular to the spin axis. The transducers holders shown on Fig. 3 were machined so that the transducer cases were held rigidly and positioned so that a line through the centerline of the case would be parallel to the axis of rotation of the shaft. Each diaphragm of the B transducers was examined through a microscope to determine if any deviation existed in perpendicularity between diaphragm and case. None could be observed. The construction of the A transducer is such that the diaphragm is internal and cannot be seen.

TEST RESULTS

A summary of the test results is presented on Table 2. The A transducers were run only on center line since their physical configuration precluded installation at various radii due to space limitations. The B1-B4 transducers are about 0.6 centimeter diameter and were installed and tested at various radii. However, the B5 transducer had a diameter of 1.3 centimeters and could be installed only on centerline.

None of the seven pressure transducers when rotated on centerline exhibited a sensitivity change of more than 1 percent at rotational speeds up to 23 000 rpm. The B3 zero shift was almost 3 percent and B4 zero shift about 2 percent of full scale. The other five transducers had zero shifts of well below 1 percent of full scale. These zero shifts are shifts in zero pressure output due to rotation and are not related to the residual zero pressure outputs of the various transducers presented on Table 1. The data in Table 2 have been corrected for centripetal acceleration effects. The numbers

with asterisks next to them indicate repeat runs.

The data that appear in Table 2 have been graphically represented in Fig. 7 to facilitate intercomparison of results due to the positioning and centripetal acceleration effects. The $1.7 \times 10^5 \text{ N/m}^2$ range transducers, B1 and B2, have zero shifts of about 0.7 percent of full scale regardless of radial position and sensitivity shifts less than 0.15 percent. The $0.3 \times 10^5 \text{ N/m}^2$ range unit B3 has a zero shift of about 3 percent of full scale for all radial positions. The data point scatter is about the same magnitude as the nonrepeatability cited in Table 1.

The zero shift for B4 is about 2 percent of full scale for all radial positions except at a radius of 0.6 centimeter. Because of this anomaly, repeat tests were made on both B3 and B4 at the 0.6 centimeter radius. The repeat tests corroborated the original results to within the nonrepeatability of the B transducers.

The sensitivity shifts for B3 and B4 for all radial positions do not exceed 1 percent and average about 1/2 percent.

CENTRIFUGAL PUMPING

The primary purpose for the work described in this report is to determine effects of centripetal acceleration on the output of pressure transducers mounted both on and off centerline in a rotating shaft. It is therefore necessary to isolate other effects which may occur. One other effect is that due to centrifugal pumping, it is a systematic effect for which a correction can be made.

Ref. 3 presents equations for making corrections which are applicable to the work presented here since no temperature gradients exist.

Equation (1) was derived from the work presented in Ref. 1.

$$\frac{P_t}{P_o} = e^{\frac{\pi N^2}{1800gRT} [r_t]^2} \quad (1)$$

P_t pressure at transducer

P_o pressure at centerline

N rotational speed, rpm

g acceleration due to gravity (9.81 ms^{-2})

R universal gas constant ($8.31 \times 10^3 \text{ J mole}^{-1} \text{ K}^{-1}$)

T temperature, K

r_t distance from centerline to transducer, m

Using the following data

$$N = 23 \text{ 000 rpm}$$

$$r_t = 0.6, 1.3, 1.9 \text{ cm}$$

$$T_r = 294 \text{ K}$$

P_t/P_o was determined to be:

$\frac{P_t}{P_o}$	Radius, cm
1.0014	0.6
1.0056	1.3
1.0125	1.9

A centripetal correction was also required on the reference side of the transducer because the reference side was vented to atmospheric pressure 0.6 centimeter off centerline as shown in Fig. 4. All tabulated results presented in this report have been corrected for centrifugal pumping and therefore represent only effects due to centripetal acceleration.

CONCLUDING REMARKS

Tests on selected pressure transducers have demonstrated that, when subjected to centripetal accelerations up to 11 200 g at a rotational speed of 23 000 rpm, the transducer calibrations differ somewhat from their static calibrations by amounts depending more on the full scale range of the transducers than on the centripetal forces imposed on them. Centerline installation results in zero shifts and sensitivity shifts which are much the same as those resulting from radial positioning.

Centrifugal pumping effects are significant at the g forces encountered in this test and must be taken into account to insure accurate pressure measurements.

REFERENCES

1. Liebert, C. H., and Pollack, F. G. 1974. "Flow Measurement in Base Cooling on Air Passages of a Rotating Turbine Blade," NASA Tech Note D-7697.
2. Pollack, F. G., and Liebert, C. H. 1972. "Rotating Pressure Measuring System for Turbine Cooling Investigations," NASA Tech Memo X-2121.
3. Michel, D. J., Ginsburg, A., and Mizisin, J. 1952. "Experimental Investigation of Flow in the Rotating Passages of a 48-Inch Impeller at Low Tip Speeds," NACA Rept. Memo E51D20.

TABLE I. - STATIC, NONROTATING PERFORMANCE PARAMETERS OF ALL TRANSDUCERS TESTED

Mfg.	Serial number	Range, N/m ²	Residual zero, % F.S.	Nonlin., % F.S.	Hyst., % F.S.	Nonrep., %	Sensitivity *	Exc. volt, V d.c.	Physical configuration and size
A	1	4×10^5	27.50	1.75	0.46	4.05	0.56 V/V	15	Rectangular parallelepiped 8x2.5x1.3 cm
A	2	0.3×10^5	142.00	0.12	0.12	0.09	0.34 V/V	15	Rectangular parallelepiped 2.8x2.5x1.3 cm
B	1	1.7×10^5	1.00	0.34	0.01	0.08	9.48 MV/V	7.5	Cylinder 0.6 cm diam. 2 cm long
B	2	1.7×10^5	-1.60	0.35	0.03	0.05	8.96 MV/V	7.5	Cylinder 0.6 cm diam. 2 cm long
B	3	0.3×10^5	-3.80	0.32	0.17	0.63	2.64 MV/V	20	Cylinder 0.6 cm diam. 2 cm long
B	4	0.3×10^5	4.20	0.25	0.09	0.71	2.15 MV/V	20	Cylinder 0.6 cm diam. 2 cm long
B	5	1.7×10^5	0.34	0.51	0.06	0.00	9.48 MV/V	7.5	Cylinder 1.3 cm diam. 2 cm long

* Sensitivity is defined as output voltage at full scale pressure per unit excitation voltage.

TABLE 2. - CHANGES IN ZERO AND SENSITIVITY FROM 0 TO 23 000 RPM
FOR PRESSURE TRANSDUCERS A AND B INSTALLED ON
CENTERLINE AND AT VARIOUS RADII

Mfg.	Serial number	Range, N/m^2	Centripetal acceleration, g 's	Radial position	Zero shift, % F.S.	Sens. shift, %
A	1	4×10^5	0	Centerline	0.13	0.94
A	2	0.3×10^5	0	Centerline	0.28	0.82
B	1	1.7×10^5	0	Centerline	0.70	-0.08
			3 700	0.63 cm	0.57	0.09
			7 500	1.27 cm	0.59	0.12
			11 200	1.90 cm	0.69	0.14
B	2	1.7×10^5	0	Centerline	0.59	-0.08
			3 700	0.63 cm	0.60	-0.04
			7 500	1.27 cm	0.45	-0.02
			11 200	1.90 cm	0.45	-0.08
B	3	0.3×10^5	0	Centerline	2.89	-0.22
			3 700	0.63 cm	2.86*	-0.52*
					3.38	-0.42
			7 500	1.27 cm	2.95	-1.04
B	4	0.3×10^5	0	Centerline	2.12	-0.18
			3 700	0.63 cm	3.33*	-0.57*
					3.48	-0.55
			7 500	1.27 cm	1.61	-0.42
B	5	1.7×10^5	0	Centerline	1.61	-0.60
					0.41	0.06

*Repeat runs.

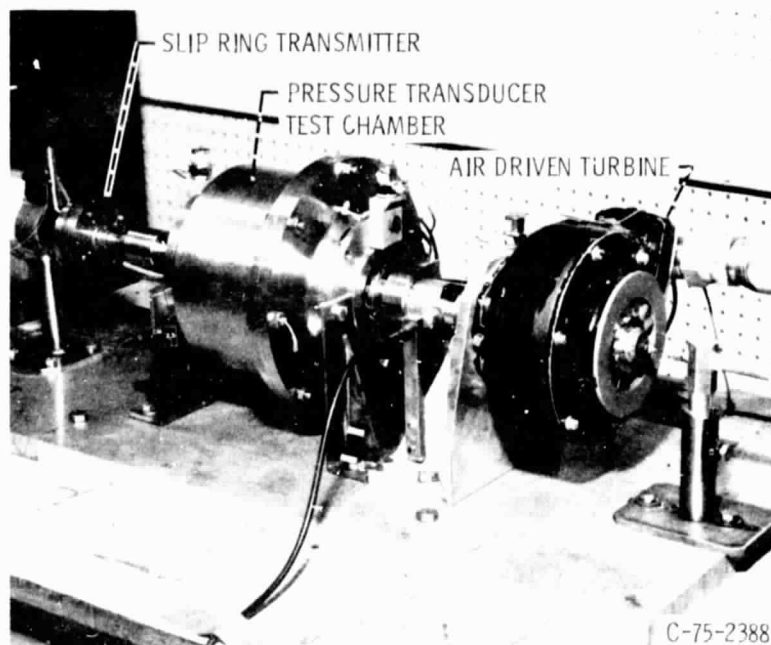


Figure 1. - Spin apparatus.

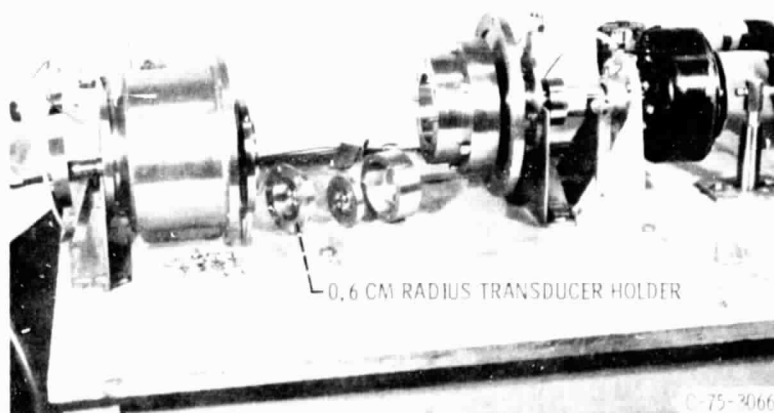


Figure 2. - Partially assembled facility showing B transducer.

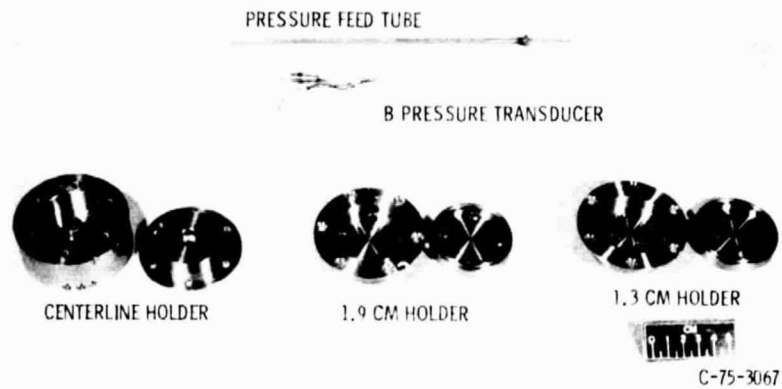


Figure 3. - Center line, 1.3 and 1.9 cm radius transducer holders, one of the B transducers tested, and pressurization tube.

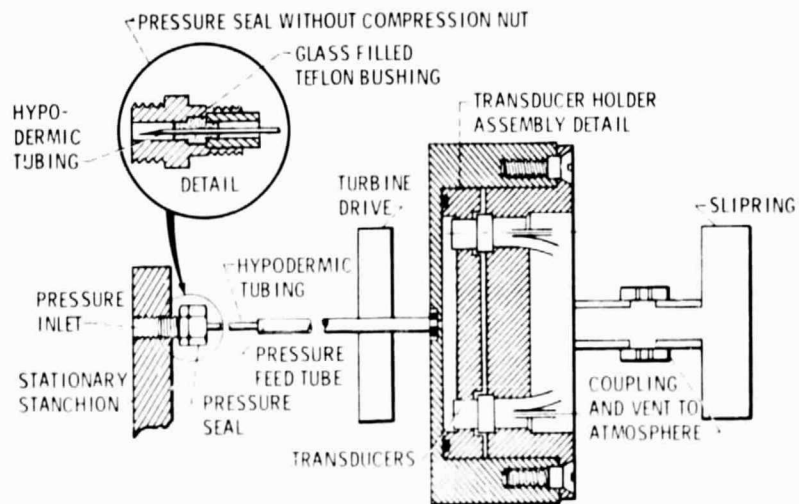


Figure 4. - Schematic of spin test apparatus with details of pressure seal and transducer holder assembly.

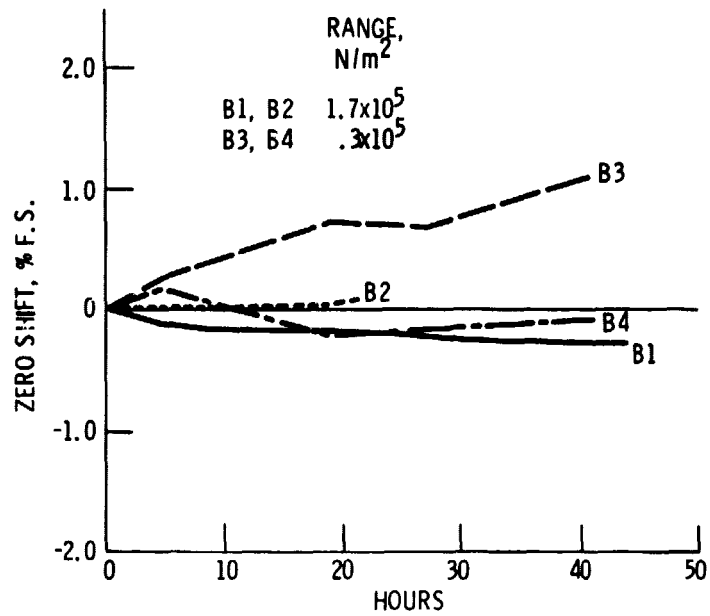


Figure 5. - Time change in zero output with atmospheric pressure on both primary and reference sides of four B transducers.

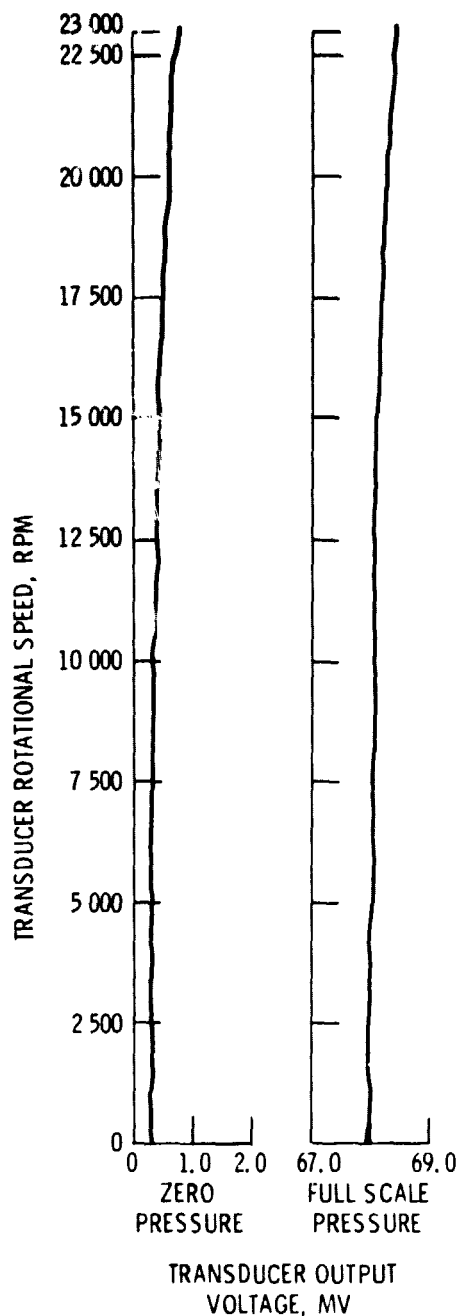


Figure 6. - Tracing of B2 transducer X-Y plot. Transducer installed on center line. Not corrected for centrifugal pumping.

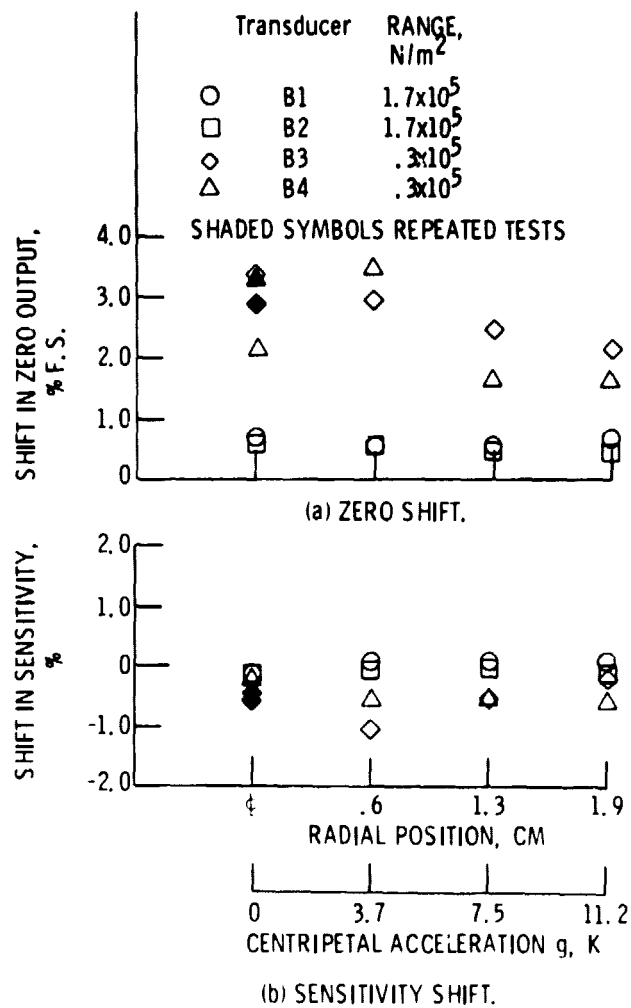


Figure 7. - Changes in zero and sensitivity from 0 to 23,000 rpm for B transducers installed on center line and at various radii.